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To Mr. F.J. Kee
Director of Research

VEHICLE PROPULSION BY LIQUID NITROGEN

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Extremely high pressures can be generated by vaporizing liquid nitrogen using heat extracted from the environment at ambient temperatures. Development of a vehicle propulsion system operating on high pressure gas generated from an onboard store of liquid nitrogen could create a significant new electrical load for Hydro in the power required to produce liquid nitrogen. In this report a preliminary analysis of this idea is reported, which suggests a) that liquid nitrogen could be as effective as the most advanced batteries currently under development in storing electrical energy for vehicle use, b) that the economics of LN_2 for vehicle propulsion may be attractive to consumers.

INTRODUCTION

Heating liquid nitrogen (LN_2) in a confined space can generate extremely high pressures. If a sample of LN_2 at its atmospheric pressure boiling point of 77°K is sealed in a (strong!) container, allowing the container to warm to 0° centigrade will generate a pressure of nitrogen gas of ~65 MPa (~10,000 psia). The only energy required to generate this pressure from LN_2 is low grade heat which can be extracted from the environment. This observation has recently led to the speculation that vehicle propulsion might be possible by operating a reciprocating or turbine engine on high pressure nitrogen gas generated by vaporizing LN_2 with heat extracted from the air/1/.

The significance of this speculation to Hydro lies in the energy required to produce LN_2. Assuming the compressors used to produce LN_2 will be electrically powered, a significant electrical load would result if a fleet of LN_2 vehicles were in

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operation. The LN_2 can be thought of as an alternative to batteries as a means of storing electrical energy for vehicle use.

In this report, a preliminary evaluation of the technical and economic feasibility of this idea is presented which suggests that further investigation is warranted.

ENERGY STORAGE EFFICIENCY

The minimum amount of mechanical work that is required to liquefy nitrogen by an ideal process is approximately 700 kJ/kg of LN_2. It can be shown from the laws of thermodynamics that this is exactly equal to the amount of work that can be extracted by vaporizing the LN_2 and bringing it back up to the original temperature. Consequently, there is no fundamental thermodynamic restriction which requires that the efficiency of LN_2 as an energy storage medium must be less than 100%.

If air is used as the source of nitrogen to make LN_2, a small amount of work (50 kJ/kg) will be required to separate nitrogen from the other components of air. This energy is not recoverable when the nitrogen is vaporized and returned to its original temperature. Use of air as a source for LN_2 then slightly reduces the theoretical maximum efficiency of LN_2 as an energy storage medium, to approximately 93%.

Practically, the machinery used for liquefaction and the motor used to power a vehicle will operate in a less than ideal manner. Currently, good large-scale liquefaction plants consume about 1890 KJ per kg of LN_2 produced/2/. This corresponds to an efficiency of (750/1890 x 100) = 40%. The efficiency of a portable LN_2 motor suitable to power a vehicle is more difficult to estimate as no such motor is available at present. However, turbines for recovery of energy from high pressure gas streams show efficiencies of 75 to 88% in industrial processes on "small or moderate streams"/3/. With this in mind, an assumed efficiency of 50% for the vehicular LN_2 motor seems not unreasonable, leading to an overall efficiency of conversion of the energy consumed by the liquefaction plant to propulsive work done in the vehicle of 20% (0.40 x 0.5 x 100).

For comparison, the efficiency of conversion of primary energy source (gasoline) to propulsive work in a conventional vehicle is in the range 15 to 25%/4/. For the LN_2 vehicle, the efficiency of conversion of primary energy source to propulsive work will be the efficiency of the previous paragraph (20%), multiplied by the efficiency of the power station which produces the electrical energy to drive the liquefaction plant. If the electric power station is oil fired, with an overall

efficiency of about 33%, then the LN_2 propulsion system is plainly less energy efficient (6%) than the direct propulsion of vehicles by oil derived fuels. However, if the liquefaction plant is powered from a low cost, non-portable source such as a nuclear or hydro-electric power station, the efficiency calculated above (20%) will be shown below to be sufficient to make LN_2 propulsion economically competitive.

COMPARISON TO OTHER PROPULSION SYSTEMS

a) Range

A fundamental parameter in determining the useful range of a vehicle is the amount of propulsive work which can be obtained per kg of energy storage medium. In Table I, the value of this parameter for various energy storage options is shown.

TABLE I

COMPARISON OF ENERGY STORAGE MEDIA

Energy Storage Medium	Specific Propulsive Work (W-hr/kg)
Hydrogen (Liquid)	7880
Methane	3080
Gasoline	2680
Diesel	2540
Aluminum-Air Battery	382
Iron-Air Battery	180
Hydrogen (Hydride)	130
Lithium-Aluminum-Iron-Sulphur Battery	126
Fuel Cell (H_2/Cl_2)	110
Sodium-Sulphur Battery	110
Liquid Nitrogen	97
Zinc-Chloride Battery	95
Nickel-Zinc Battery	73
Nickel-Iron Battery	58
Lead Acid Battery	49
Flywheels	13

The assumptions made in deriving this table are the following:

i. The efficiency of conversion of chemical energy to propulsive work from fuels such as gasoline or hydrogen will be 20%/4/.

ii. The efficiency of conversion of electrical energy stored in batteries or kinetic energy stored in a flywheel to propulsive work will be 90%.

iii. The efficiency of conversion of energy stored in LN_2 to propulsive work will be 50% (see previous section).

iv. The performance of exotic technologies (other than LN_2) will improve up to 1985 at the rate estimated in/5/.

Several conclusions can be drawn from the table:

i. The distance travelled per unit mass of energy storage by LN_2 vehicles will be considerably less than that of vehicles operating on chemical fuels (except when that chemical fuel is hydrogen stored as a hydride).

ii. The distance travelled per unit mass of energy stored by LN_2 vehicles will be competitive with that of vehicles using exotic batteries or fuel cells, and in fact greater than most.

iii. The distance travelled per unit mass of energy storage by LN_2 vehicles will be twice as great as that of vehicles using conventional lead-acid batteries.

b. Cost

The cost of electrical energy to drive a liquefaction plant can be calculated from the value given earlier for the amount of work required per kg of LN_2 produced (1890 kJ/kg). Assuming electrical energy can be converted to mechanical work with 90% efficiency, and that electrical energy costs 2c/KWH, the cost of electrical energy per kg of LN_2 produced will be $(0.02 \times 1890) \div (0.9 \times 60 \times 60) = 0.012$ \$/kg.

For estimation of the capital cost of LN_2 production, the cost of a large scale "turn-key" liquefaction plant has been obtained from Sulzer. Their approximate price for a 5000 tonne per day plant is 100 million Sw Fr (~65 M\$). The capital cost of such a plant per kg of LN_2 produced, assuming a 25 year plant life (equivalent to a 4% per year depreciation) and 10% interest rates, will be $0.14 \times 65 \times 10^6 \div 365 \times 5 \times 10^6$ = 0.005\$/kg.

For comparison with conventional fuels, the above numbers need to be scaled according to the useful propulsive works available from each fuel. Using the values of Table I, the appropriate scaling factor for comparison with gasoline is 2680 ÷ 350. Using this scaling factor, the sum of the electrical and capital costs of LN_2 (0.017\$/kg) is equivalent to a gasoline

price of 0.13$/kg or 0.09$/L. Currently, the production and refining costs of gasoline, based on the standard OPEC price of $34 (US) per barrel, are approximately 0.30/L (Gulf Oil figures, Canadian dollars).

In practice, costs for LN_2 production will be increased because of labour costs, maintenance requirements in the production facility, LN_2 losses in storage, etc. However, even if such extra charges double the cost of LN_2, it appears that production costs for LN_2 will be slightly more than half the current production cost of gasoline on a per energy basis.

c. Refuelling

As LN_2 is a liquid, refuelling will be no more complicated than fuelling a conventional vehicle. In contrast, battery powered vehicles would either involve long recharging times once their power was exhausted or complicated mechanical and electrical design to allow battery pack changeover.

d) Safety

Liquid nitrogen propulsion can be expected to have a significant safety advantage over other propulsion systems. In contrast to almost all other energy storage options, the use of LN_2 will require no inflammable, corrosive or toxic chemicals. In addition, as no temperatures above ambient are involved, ignition of outside materials will not be a problem. This may make LN_2 vehicles particularly attractive for use in hazardous environments (mines, production plants for explosive chemicals, etc).

Use of LN_2 will introduce two extra hazards compared to most other energy storage media: danger of explosion due to the extremely high pressures employed and danger of freezing injuries from unintended contact with LN_2. The first of these hazards can be minimized by careful design to ensure that all LN_2 containing components are protected by safety valves or burst discs. The danger of freezing injuries in accidents, while important, should be less of a hazard than that of fire in gasoline powered vehicles due to the formation of an insulating nitrogen vapour layer between LN_2 and warm surfaces (such as skin) on initial contact.

e) Pollution

The exhaust from LN_2 vehicles will be nitrogen gas at a temperature slightly below ambient. As nitrogen gas is already the major component (78%) of air, no toxic effects will result.

DEVELOPMENT OF AN LN_2 PROPULSION UNIT

Liquid nitrogen is currently produced and used on a large scale in industry. As outlined in the previous section, no breakthroughs in the production of LN_2 appear to be necessary to make LN_2 vehicles economic. However, an LN_2 propulsion system for vehicle use will have to be developed.

A sketch of the essential components of an LN_2 propulsion system is shown in Figure 1. No detailed design study of such a system has as yet been carried out; however, a preliminary examination of the problem has suggested the following comments:

i. Use of small pump to inject LN_2 into the flash evaporator will allow the use of an LN_2 tank at atmospheric pressure, greatly reducing the strength requirements (and therefore weight) of this bulky tank.

ii. Use of a liquid "warmant" (analogous to coolant) to transport heat from ambient air to the flash evaporator and reheater will greatly reduce the size of these two components due to the higher rate of heat transfer from a liquid compared to a gas. As the flash evaporator and reheater will have to contain extremely high pressures, reductions in their size will be very significant in weight reduction.

iii. The size of the air-to-"warmant" heat exchangers will not be excessive. The amount of heat extracted from the air by a 50% efficient LN_2 motor will be less than three times the amount of work done to drive the vehicle. In contrast a gasoline powered vehicle (15 to 25% efficient) rejects as heat approximately five times the amount of work done to drive the vehicle. Consequently, for a similar temperature difference between warmant and air in the LN_2 vehicle to that found between coolant and air in a gasoline powered vehicle, the air heat exchanger in the LN_2 vehicle will be smaller than the air heat exchanger (radiator) of a conventional gasoline vehicle. Conversely, using an air heat exchanger similar in size to a conventional radiator, the temperature difference between the warmant and air can be reduced from the 90°C typical of conventional vehicles to approximately 50°C.

iv. A double expansion engine (at least) will be required to extract energy efficiently from the LN_2. In a single expansion engine, the temperature drop on expansion of the nitrogen gas would result in reliquefaction of the nitrogen if the expansion ratio of the engine exceeded (approximately) a factor of four, wasting a considerable amount of the work available.

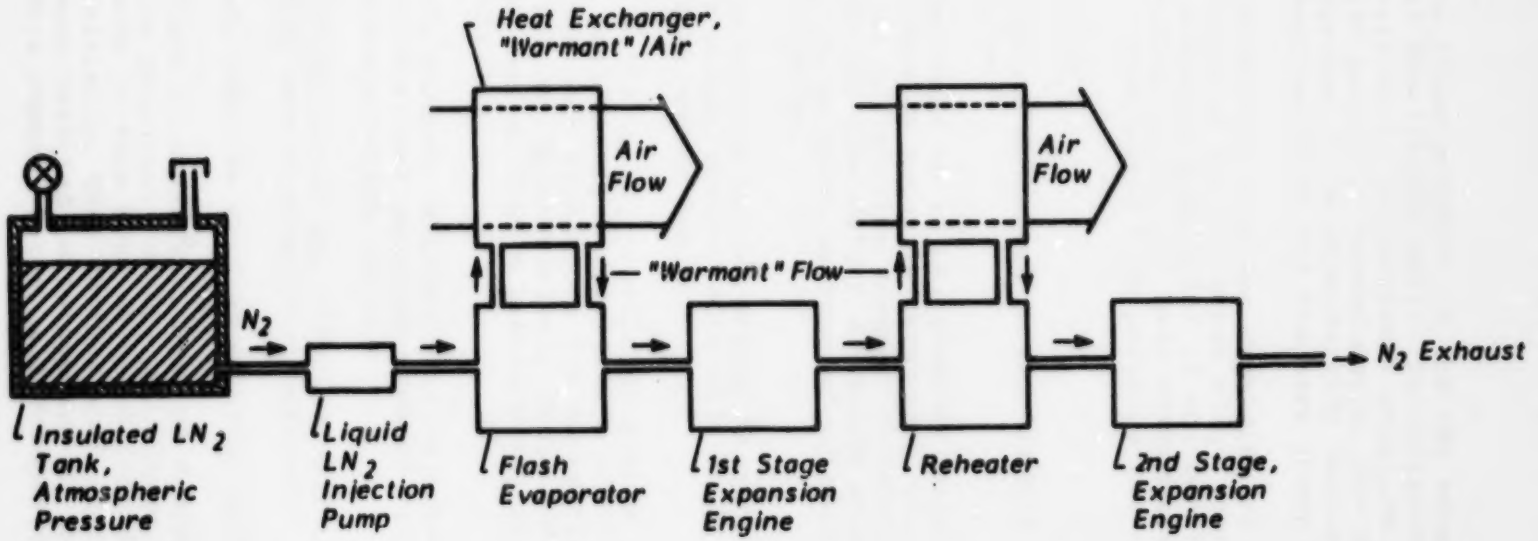

FIGURE 1

SCHEMATIC DIAGRAM - LN_2 PROPULSION SYSTEM

v. The inlet pressure in the LN_2 expansion motor will be ~65 MPa (10,000 psi). In contrast, the average cylinder pressure in conventional gasoline engines is around 1 MPa (150 psi)/6/. Consequently, the LN_2 expansion motor is expected to be considerably smaller than a conventional gasoline motor for the same power output.

vi. Outstanding problems remaining to be considered in the design of the LN_2 motor are: lubrication (are suitable lubricants available? if not can they be developed?) deicing of the air heat exchangers, and suitable materials for containing high pressure gas at low temperatures.

CONCLUSIONS

The arguments presented in this report suggest the following conclusions:

i. The range of an LN_2 powered vehicle, if a 50% efficient expansion motor is developed, will be about the same as that of vehicles powered by exotic batteries or fuel cells for the same weight of energy storage, and approximately twice as great as that of vehicles using lead-acid batteries.

ii. Per unit of useful energy stored, LN_2 can be manufactured at a cost slighty more than half that of gasoline on an equal energy basis.

iii. A suitable LN_2 propulsion system has yet to be developed. A preliminary investigation of this problem has indicated that heat exchangers for extraction of heat from the air will not be excessively large and that the LN_2 motor will be smaller than a gasoline engine of comparable power output.

iv. LN_2 powered vehicles will be inherently safer than either conventional gasoline powered vehicles or other exotic transportation options.

v. Refuelling of LN_2 vehicles will be much faster than with most exotic propulsion options.

vi. LN_2 vehicles will be entirely pollution free.

These conclusions, based on a preliminary examination of the potentials of LN_2 propulsion, suggest that further work in this area could be fruitful to Ontario Hydro. Initially, that further work should take the form of a more detailed investigation of the areas touched on in this report; later, a development program will be

necessary for the LN_2 propulsion system which could be funded by some combination of Ontario Hydro, the Provincial Government, the Federal Government, EPRI and the automotive industry.

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